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HEALTH MANAGEMENT AND SUSTAINMENT TRANSFORMATION IN THE U.S. AIR FORCE (PREPRINT)

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14. ABSTRACT
The Air Force Research Laboratory (AFRL), along with its many research partners, is actively engaged in aiding the transformation of the Air Force's sustainment practices. While the concept of health management has been discussed in the research community for some time now, the U.S. Air Force has faced many challenges which inhibit the transition of these technologies. However, times are changing in our Air Force. Transformation which is occurring at all levels of the Air Force seeks to eliminate the barriers which stand in the way of implementing Integrated Systems Health Management (ISHM). This paper will briefly discuss the various Air Force (AF) sponsored transformation activities and how these programs represent real opportunities to transition technologies which the health management community has been working so diligently on. The remaining portion of the paper will describe AFRL's ISHM vision and focus on the authors' own research in embedded sensing systems.

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ABSTRACT

The Air Force Research Laboratory (AFRL), along with its many research partners, is actively engaged in aiding the transformation of the Air Force's sustainment practices. While the concept of health management has been discussed in the research community for some time now, the U.S. Air Force has faced many challenges which inhibit the transition of these technologies. However, times are changing in our Air Force. Transformation which is occurring at all levels of the Air Force seeks to eliminate the barriers which stand in the way of implementing Integrated Systems Health Management (ISHM). This paper will briefly discuss the various Air Force (AF) sponsored transformation activities and how these programs represent real opportunities to transition technologies which the health management community has been working so diligently on. The remaining portion of the paper will describe AFRL's ISHM vision and focus on the authors' own research in embedded sensing systems.

U.S. AIR FORCE TRANSFORMATION

Since the Cold War the way in which the Air Force wages war has changed dramatically. Today's Air Force is now an expeditionary force engaged in multiple contingencies and deployments simultaneously. This shift in paradigm requires changes in the logistical operations and support processes so the Air Force can respond quickly with the right equipment to effectively support the warfighter. This shift, however, was not unique to the Air Force and in 2003 the Office of the Secretary of Defense (OSD) charged each of the U.S. military services to optimize support to the forward-deployed warfighter [1].

Expeditionary Logistics for the 21st Century (eLog21)

The Air Force has embarked on a campaign to make the necessary changes to better support the warfighter. The Expeditionary Logistics for the 21st Century (eLog21) Campaign seeks to develop and implement transformational concepts, processes, systems, and policies to deliver dependable, effective, and efficient Agile Combat Support (ACS) to the 21st century expeditionary aerospace force. The vision is to provide an integrated Air Force-wide logistics system that delivers consistent capabilities to the warfighter. The eLog21 Campaign has two goals: 1) to increase equipment availability by 20% and 2) to reduce annual Operations and Support (O&S) costs by 10%, both by fiscal year 2011 [1]. To the typical ISHM researcher the eLog21 Campaign is a welcome partner as it seeks to address the very deficiencies that hamper ISHM implementation in today's fleet –namely the archaic data systems that date back to the 50's which still support Air Force systems today. While we ultimately plan to integrate diagnostic and prognostics capabilities into the design of future weapon systems, we first must develop and demonstrate these capabilities on legacy systems. The reason for this is that many of the technologies are fairly immature and require demonstration in an operational environment to bring the technologies to fruition. Many of these technologies are

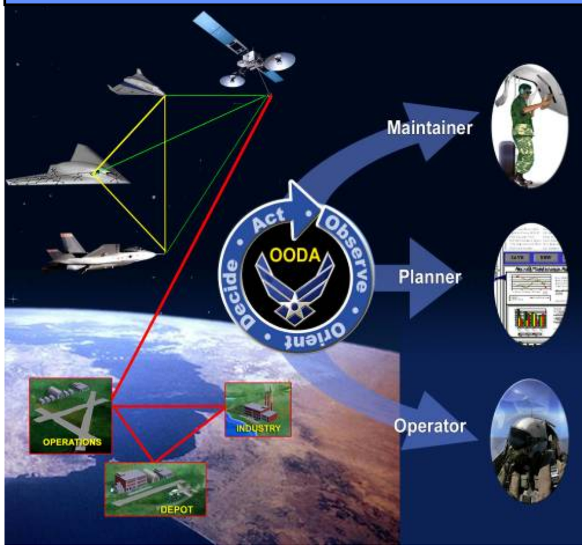
still too high risk to be considered in new systems. Therefore, risk reduction demonstrations will be necessary in legacy systems. However, due to the expense of system modifications there is no doubt that the implementation of ISHM capabilities into these legacy systems will first be done off-board in ground support data systems. Implementation of on-board capability will only occur in cases where the ground demonstrations show benefits which outweigh the high expense of retrofits. Many researchers pay little attention to the transformation occurring in these data support systems. But they must realize that these data systems may be the first opportunity to transition the diagnostic and prognostic capabilities they are developing.

Condition Based Maintenance Plus Initiative

A major component of the eLog21 Campaign is the Condition Based Maintenance Plus (CBM+) initiative. In November of 2002 the Deputy Under Secretary of Defense for Logistics and Material Readiness directed the Military Departments and Defense Agencies to examine, evaluate, develop and implement CBM+ enabling technologies and process improvements. The policy stated that "CBM+ shall be implemented to improve maintenance agility and responsiveness, increase operational availability, and reduce life cycle total ownership costs" [2].

Condition-Based Maintenance (CBM) is defined as "a set of maintenance processes and capabilities derived from real-time assessment of weapon system condition obtained from embedded sensors and/or external test and measurements using portable equipment. The goal of CBM is to perform maintenance only upon evidence of need" [3]. Condition-Based Maintenance Plus (CBM+) is CBM ***enhanced*** by system reliability analysis and prognostic capabilities. The CBM+ approach to maintenance is based on evidence of need before failure occurs or the evidence of a need forecasted by analyzing data collected during system operation by integrated sensors. CBM+ is supported by automated maintenance information systems that seamlessly integrate with other logistics systems. Therefore, Conditioned-Based Maintenance Plus leads to more efficient maintenance, increased readiness, and significant cost savings associated with smaller logistics footprints. Enabling technologies for CBM+ implementation include embedded sensors and diagnostics, prognostics, data analysis, integrated information systems and automated test equipment. Clearly, CBM+ is yet another stepping stone towards achieving ISHM capability.

Enabling State Awareness & Prognosis in AF Operations to assure maximum mission capability, increase availability and curtail growing O&S costs



- Provide maintainer total system health information
- Enable maintenance and mission planners to optimize asset allocations
- Enable operators to assess system capability during the mission (e.g. ability to "hot swap" sorties)

Figure 1. Integrated Systems Health Management Concept.

INTEGRATED SYSTEMS HEALTH MANAGEMENT

AFRL's vision of Integrated Systems Health Management is depicted in Figure 1. This graphic shows real time communication links between platforms and connectivity to the operations base, the depot and industry. This concept brings the idea of net-centric warfare to the next level by incorporating the real time health status of assets into the operations decision loop. This decision loop is often referred to as the "OODA" loop which stands for Observe – Orient – Decide – Act. Consideration of the real time health status of assets can provide a variety of benefits to the warfighter. To fully appreciate how this vision will impact the warfighter one must consider the perspective of three primary warfighter roles: the maintainer, the planner and the operator. To the maintainer this real time capability will provide advanced notice of the condition of an asset before it returns to base. This will enable the maintainer to be prepared with the correct tools and real time training needed to quickly turn the asset. Quicker turn times translates into higher availability to the commander. This concept applies to all levels of maintenance – operations, intermediate and depot.

Both mission and maintenance planners will also benefit from this capability. With ISHM the mission capability of an asset will no longer be a black and white metric. The planners will have a more defined understanding of the capability of an asset. This will allow the Mission Planner maximize the probability of mission success by matching to the mission. Knowing the real time system status will also aid the maintainers and maintenance planners by enabling autonomic logistics (e.g. parts ordering) and maintenance scheduling. The final game changing capability that ISHM will enable is sortie 'hot swapping'. To better explain this concept, imagine a mission where two assets are set out to engage two separate targets; one

target being further away than the other. Suppose one of the assets experiences some sort of failure –not necessarily a catastrophic failure but perhaps one that significantly restricts the range. The maimed asset can no longer engage its target. With today's capability the mission would be aborted. But with ISHM this does not necessarily have to be so. The commander could immediately know of the problem and could analyze the maimed asset's ability to engage the closer target. If the simulated scenario pans out the commander could then switch the mission profiles of the two assets mid-mission to effectively engage both targets as initially intended. To the commander this translates into higher mission effectiveness and even improved survivability in some cases.

Real Time State Awareness

The ISHM vision described above requires the integration of a number of technologies. The ISHM scope includes airframes as well as space systems - satellites, rockets, and space vehicles which will provide access to space. Technologies include integrated sensing systems, data fusion, advanced diagnostics and prognostics algorithms, state-of-the-art control theory and even advanced training and data presentation concepts. Various teams are engaged in the development of these technologies across AFRL. The objective of real time state awareness is to determine the current health condition of the entire weapon system in real-time and assess its performance capability. The approach is to assess the condition of each critical sub-system to include structures, propulsion, and flight controls and determine the net degradation on system's performance. This will be accomplished via sensors, usage/environmental models, data models, physics-based models and decision making reasoners.

Figure 2 represents the ISHM process. The gray box encompasses Real Time State Awareness (RTSA). RTSA has both on-board and off-board elements. The on-board component includes embedded sensing systems which will be used as a first indication that the system or sub-system is operating in an anomalous condition to indicate damage states in real time. The ability to detect damage using embedded sensing is not viewed as a replacement for traditional non-destructive inspection techniques such as ultrasonic and eddy current capabilities. Rather, embedded capabilities will be an indication that further investigation of the system is needed to ensure nominal performance of the system. In the event of an anomaly indication, the maintainer would use field inspection technologies to further investigate the damaged area and make an assessment of the overall health of the AF system. If a system anomaly is observed across the fleet, depot level inspection tools with high resolution and accuracy could be employed to identify the root cause of the system failures. Also, depot level inspections, the mainstay of how the U.S. Air Force maintains it fleets today, is critical for the realization of the ISHM vision as it will provide the benchmarking required to 'fine-tune' the diagnostic and prognostic codes needed to predict failure.

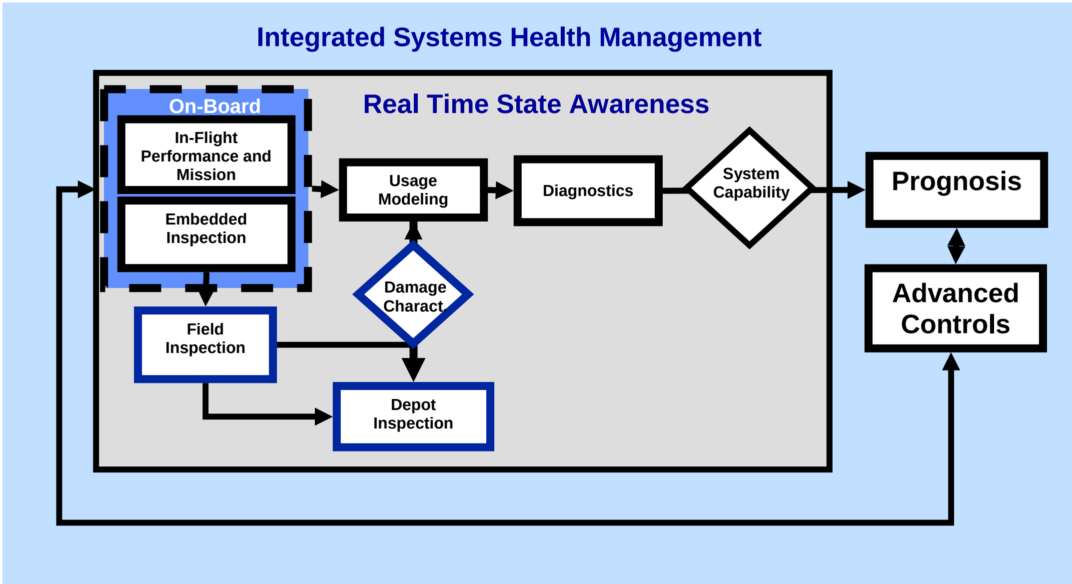


Figure 2. Real Time State Awareness Strategic Approach.

Realization of ISHM requires that the actual usage of the system be recorded and stored for analysis. The damage indications and characterizations obtained from the on-board and off-board sensing systems are then combined with the usage information. The diagnostics component takes this data and determines the systems health status, which is the output of the RTSA process. This output serves as input into the prognosis function. Prognosis is where life prediction algorithms will use the data provided by RTSA to determine an asset's ability to perform a given mission. Also, Prognosis will determine if the asset can continue to operate until the next maintenance cycle, thereby skipping a maintenance cycle. The Advanced Controls element interfaces with the Prognosis component. Together they negotiate probable courses of action. When a course of action is determined, it is up to the Advanced Controls element to execute that action. This is depicted in the figure by the feedback loop to the system in dark blue. Ultimately the capabilities depicted in the black boxes in Figure 2 will be embedded in the system to enable the capabilities described in the previous section and in Figure 1.

Embedded Sensing Systems

The authors' research is currently centered on the development of embedded sensing systems. Research areas include: 1) Development of highly sensitive, robust and reliable sensors, 2) Integration and installation of these sensors into current Air Force systems, and 3) Efficient collection, storage and transmission of sensor data for in-flight analysis or post-flight downloading and evaluation. Sensing applications include a variety of applications including aircraft structural elements, turbine engines and thermal protection systems for space and re-entry vehicles. Each potential application has its own unique challenges associated with the integration of sensing technologies; however, there are technology areas such as the wireless transmission of data that cut across all the potential Air Force (AF)

applications. The following paragraphs will present on-going AF sponsored programs that seek to develop specific capabilities as well as the potential applications for these capabilities.

Given that U.S. military aircraft are being used, in many cases, longer than their original design life, it is imperative that capabilities be developed to monitor the structural integrity of critical aircraft structural components. Several interrelated capabilities are required to realize the overall ISHM capability. Technologies are sought which will allow sensors to be embedded into areas which do not have easy maintenance access. These technologies will eliminate the need for labor-intensive teardowns to do visual inspections. There are some applications which require the monitoring of wide areas, usually at lower resolution, while other more critical areas require accurate monitoring for cracks. AFRL's efforts spans all the areas mentioned. But first and foremost AFRL is managing an effort which seeks to model the required application. Modeling tools have been developed that use the structural design as an input to analyze resonant frequency modes and determine the optimum placement points on the structure to collect accelerometer data. Accelerometer data is collected and analyzed during cyclic loading to detect the initiation and growth of structural cracks. This dynamic systems model approach minimizes the number of sensors required for the application. Successful development of this technology will provide AF maintainers the capability to identify, locate, and quantify defects that have to be investigated prior to subsequent mission flights. This capability will dramatically increase aircraft safety and could result in reduced inspections.

AFRL efforts supporting structural health monitoring include developing distributed sensing networks of fiber optic bragg gratings to allow light weight, high density sensing. A system has been developed which is capable of reading a thousand gratings per fiber with spacing as small as 1.5 cm center-to-center with a gage length of 1 cm. Such a system could be used to monitor deflection and loading in critical structural areas of the air frame. This information on the actual usage could also be used to update the models used to accurately determine structural life. AFRL is also investigating methods to increase the temperature capability of quartz fibers for higher temperature structural applications. Two methods of creating Bragg gratings into the fibers are being investigated - the use of electric arcs and fempto-second lasers. Both techniques have shown excellent preliminary results for survival at 1000^{o}C. Given the potential for multiplexing, light weight and immunity to EMI, these sensors show great promise for high density use in a multitude of high temperature applications.

AFRL is also interested in developing sensors that can operate in the extreme environment (>1000°C) of aircraft turbine engines, hypersonic and thermal protection systems. There are two main goals of this technology push with respect to turbine engines; 1) Create the capability to monitor critical engine operating parameters which will give turbine engine designers and life prediction experts the data needed to validate and further refine current engine life prediction models, and 2) Create the capability to monitor the integrity of engine critical components during flight. The Air Force has identified a need to measure operating parameters such as engine pressure, combustion emission, and component surface temperatures. In addition, the capability to monitor blade tip clearance, bearing

health, thermal barrier coating health and component strain is critical to realize the benefits of an in-situ engine health monitoring system. With respect to thermal protection systems (TPS), the AF desires the capability to monitor surface temperature, component vibration, surface oxidation and TPS seal integrity. It is believed that as these TPS capabilities are combined, AF maintainers will have a methodology to quickly determine any potential damage locations, resulting in a dramatic decrease in the amount of time currently required to perform TPS integrity validation and thus increase space operation vehicle availability.

AFRL is currently sponsoring a number of programs aimed at developing state-of-the-art sensors that can operate in the extreme environments imposed by turbine engine operation and thermal protection systems. This is an extremely challenging technical area that requires improved sensor accuracy, increased survivability and durability and decreased sensor drift. AFRL is currently investigating multi-functional thin film ceramic sensors capable of temperature, heat flux and static strain measurements. When combined with thin film antenna technology and a transceiver, one potential application for this technology is the in-situ measurement of turbine blade surface temperatures and strain which will enable model validation and blade integrity monitoring. Another technology under investigation is a langasite surface acoustic wave device which has already shown tremendous durability at 750ºC. This technology is promising due to its inherent wireless capability and ruggedness and is envisioned to provide temperature and pressure measurements for engine model validation and potential use in TPS structures where a thin film technology is not required. Finally, AFRL is investigating the use of a thermal spray technique to literally spray sensors onto surfaces. The sensors created in this manner are referred to as Direct-Write sensors. Because of the nature of the technology, these sensors require a substrate or part to write the sensor onto and therefore each sensor can be made uniquely for the part geometry. Furthermore, this technology can be used to “write” a sensor, leads, capacitor, and antenna system for wireless operation. The low profile of these sensors combined with their potential to be wireless makes this technology an excellent candidate for rotational applications in turbine engines.

SUMMARY

This paper has described activities underway to transform the U.S. Air Force’s support processes. The eLog21 Campaign seeks to reduce maintenance costs and increase equipment availability by providing an integrated Air Force-wide logistics system that delivers consistent capabilities to the warfighter. The eLog21 Campaign recognizes its need for diagnostic and prognostic capability in its inclusion of these technologies in the definition of the AF CBM+ initiative. While many ISHM researchers target their development towards new systems, researchers are encouraged to learn more about these transformational AF activities as these programs present near term opportunities to develop and demonstrate ISHM technologies on legacy systems using off board data systems.

The Air Force Research Laboratory’s vision for ISHM has been described from three different perspectives: the maintainer, the planner, and the operator. AFRL’s

strategic approach was also presented with special attention detailing the authors' work supporting Real Time State Sensing. Current research efforts in structural health monitoring and health sensors for harsh environments such as turbine engine and space applications have been described. The high temperature sensor work described is a high technical challenge area that requires more attention than it is currently receiving. AFRL is actively seeking partnerships to aid in the development of these critical technologies.

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